HYDRAULIC CONDUCTIVITY OF SUBSTRATES USED FOR PASSIVE ACID MINE DRAINAGE TREATMENT[1]

by

Judith L. Bolis, Thomas R. Wildeman and Helen E. Dawson[2]

Abstract. In anaerobic wetland systems that emphasize flow of acid mine drainage through the substrate, the hydraulic conductivity of the substrate material is an important variable. This paper describes results of hydraulic conductivity measurements obtained from two sets of bench scale experiments conducted in 1990 and 1991 with substrate-filled reactors that were used to treat acid mine drainage in the Clear Creek-Central City Superfund site. In 1990, the reactors were filled with an organic substrate of manure and planter soil and were subjected to three initial substrate conditions: 1) dry, 2) soaked with water for one week, and 3) inoculated and soaked with water for one week. Flow rate measurements indicated that the hydraulic conductivity of the initially dry substrate remained consistent over time, while the hydraulic conductivity of the soaked substrates increased over time. In 1991, a primarily inorganic substrate of limestone and alfalfa was tested in addition to the previously described organic substrate. Initial substrate conditions for both substrate types were 1) dry and inoculated and 2) inoculated and soaked for one week with mine drainage. Results indicate that in both the limestone and manure reactors which started with dry substrate, the hydraulic conductivity fluctuated considerably. The values for the initially dry limestone ranged from 2.1×10^{-3} - 1.3×10^{-2} cm/sec while the initially dry manure ranged from 9.9×10^{-5} - 7.1×10^{-3} cm/sec. The hydraulic conductivity was more consistent in the soaked reactors ranging from 1.3×10^{-3} - 8.8×10^{-3} cm/sec in the soaked limestone and from 3.4×10^{-4} to 6.9×10^{-3} cm/sec in the soaked manure. These results indicate that presoaking the substrate for wetlands treatment of acid mine drainage can assist in providing a more stable hydraulic conductivity and, therefore, a more consistent flow rate.

Key words: hydraulic conductivity, acid mine drainage, bench scale reactor, permeameter

Introduction

Anaerobic treatment of acid mine drainage has been found to successfully remove metals and raise pH through the bacterial reduction of sulfate to sulfides (Howard et al. 1989). This treatment method requires designing a substrate that will facilitate subsurface flow as well as optimize conditions for bacterial reduction. Typically, the effectiveness of constructed wetlands for treating acid mine drainage or other wastewater depends on the hydraulic conductivity of the substrate. Low hydraulic conductivity, caused by a build up of bacterial growth and sediment fines, may cause

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[2] Judith L. Bolis is a graduate student and Helen E. Dawson is an assistant professor in the Department of Environmental Sciences and Engineering, and Thomas R. Wildeman is Professor of Chemistry and Geochemistry in the Department of Chemistry and Geochemistry, Colorado School of Mines, Golden, CO 80401.

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short circuiting of a treatment system (Lemke 1989, Cooper 1989, Watson et al. 1989, Staubitz 1989, Trautman 1989). Specifically, in the treatment of acid mine drainage in constructed wetlands, a decrease in the hydraulic conductivity of a substrate may result in surface flow (Steiner 1989) and, thus, affect the removal efficiency of an anaerobic treatment system that depends on subsurface flow (Machemer et al. 1990). Table 1 lists the hydraulic conductivities reported in the literature for various materials that have been used in the wetlands treatment of acid mine drainage and other wastewater.

Hydraulic conductivities measured in bench scale permeameters have been found to be predictive of the hydraulic conductivities in pilot scale wetlands (Lemke 1989). Lemke measured the hydraulic conductivities of fresh and used organic substrates composed of varying ratios of mushroom compost, peat and wood shavings and determined values ranging from 3.0×10^{-4} cm/sec to 6.7×10^{-7} cm/sec. Bench scale experiments used to simulate the removal of metals from acid mine drainage (Bolis et al. 1991) suggested that hydraulic conductivity is a function of the initial condition of the substrate, i.e., dry versus soaked.

This paper compares the results of hydraulic conductivity measurements obtained in previous bench scale experiments (Bolis et al. 1991) to the results obtained from additional experiments designed to more definitively determine the influence of initial condition and time on hydraulic conductivity. The first set of experiments were conducted in 1990 with acid mine drainage from the Quartz Hill and National Tunnel sites in the Central City/Blackhawk mining district as described by Bolis et al. (1991). The second set of experiments were conducted in 1991 with acid mine drainage from the Big Five Tunnel in Idaho Springs, CO. In the latter experiments, both inorganic and organic substrates were tested in the lab and in the field. The results of the hydraulic conductivity measurements are evaluated with regards to the type of substrate and initial condition of the substrate.

Materials and Methods

1990 Experiments

Substrate hydraulic conductivity was initially evaluated using the National Tunnel and Quartz Hill mine drainage reactors. The reactors were constructed of 32 gallon plastic garbage cans fitted with PVC pipe and designed to operate without valve control in a downflow configuration (Bolis et al. 1991).

The substrate was a mixture of cow manure and top soil in a 3:1 ratio. Three initial substrate conditions were tested for both drainages. Prior to flowing mine drainage through the system, one reactor was dry, a second reactor was soaked with water for one week, and a third was inoculated and soaked with water for one week. The inoculum was a mixture of substrate from the Big Five wetland that contained sulfate reducing bacteria (Batal 1989).

Experimentation began in June 1990 and continued until November 1990. The reactors were operated in a downflow configuration with a constant head reservoir of water on top of the substrate. Flow rates were maintained at 10 ml/min for the National Tunnel drainage and 1 ml/min for the Quartz Hill drainage by adjusting the height with the effluent pipe. An upflow configuration was also evaluated later in the experimentation on both drainages.

1991 Experiments

The Big Five Tunnel acid mine drainage was used for more extensive evaluation of the hydraulic conductivity of substrates. This drainage is characterized with a pH of approximately 3.0 and metals concentrations of 50 mg/L Fe, 35 mg/L Mn, 10 mg/L Zn, and 1 mg/L Cu (Wildeman and Laudon 1989).

The four reactors used in this study were similar to those used in the previous study. Each reactor had a constant head reservoir of water on top of the substrate. Flow rates were maintained at approximately 10 mL/min adjusted by raising or lowering the effluent level.

Two types of substrate were tested in the reactors: an organic and inorganic substrate. Two of the reactors contained the organic substrate tested in 1990 composed of 75% cow manure and 25% planter soil by volume (Bolis et al. 1991). The pH of this substrate was approximately 8.7. The total amount of substrate used in each reactor was 225 lb, of which 25 lb was inoculum. The inoculum consisted of substrate from currently active cells at the Big Five pilot wetland. One of the reactors was soaked for 1 week with mine drainage prior to operation, the other was left dry.

The second set of reactors contained a primarily inorganic substrate composed of

Table 1. Hydraulic conductivity of substrates used in wetlands treatment of wastewater.

MATERIAL	HYDRAULIC CONDUCTIVITY Reported Values	HYDRAULIC CONDUCTIVITY Equivalent in cm/sec	USE	REFERENCE
Mushroom compost (unused)			acid mine drainage	Lemke 1989
lab downflow	3.50×10^{-3} cm/s	3.50×10^{-3}		
bench-downflow	3.14×10^{-3} cm/s	3.14×10^{-3}		
pilot-downflow	2.96×10^{-4} cm/s	2.96×10^{-4}		
lab-upflow	6.65×10^{-2} cm/s	6.65×10^{-2}		
bench-upflow	1.44×10^{-2} cm/s	1.44×10^{-2}		
pilot-upflow	1.38×10^{-2} cm/s	1.38×10^{-2}		
Old Natural Reed Beds	5×10^{-6} m/s	5×10^{-4}	general wastewater treatment	Referenced in Cooper and Hobson 1989
recommended United Kingdom design values	3×10^{-3} m/s	3×10^{-1}		
gravel	1×10^{-3} m/s	1×10^{-1}		
pulverized fuel ash	8×10^{-5} m/s	8×10^{-3}		
quarry rejects	1×10^{-3} m/s	1×10^{-1}		
pea gravel	8×10^{-1} m/s	8×10^{1}		
soil beds (in Europe)	2.6 m/d	3×10^{-3}	general wastewater treatment	Referenced in Watson et al. 1989
gravel beds (in Europe)	30 m/d	3.4×10^{-2}		
suggested range	30 - 864 m/d	$3.4 \times 10^{-2} - 1 \times 10^{1}$		
reed bed media range:			reed bed treatment	Referenced in Hobson 1989
clays	1×10^{-7} m/s	1×10^{-5}		
coarse gravel	1×10^{-1} m/s	1×10^{1}		
soil beds	$< 3 \times 10^{-5}$ m/s	3×10^{-3}		
homogeneous mixture (lab test)	80 m/d	9×10^{-2}	landfill leachate treatment	Staubitz et al. 1989
sorted substrate (lab test)	1600 m/d	1.8×10^{1}		

approximately 77% limestone rock, 14% alfalfa, and 9% inoculum by volume. These reactors contained a total of 260 lb of substrate composed of approximately 198 lb limestone, 37 lb alfalfa, and 25 lb inoculum. The limestone rock ranged in size from 1/8 inch to 1/2 inch. Again, the inoculum was obtained from cells at the Big Five wetland. As with the manure substrate reactors, one of the reactors was soaked with mine drainage for one week prior to operation and the other was left dry.

This experiment began in July 1991 and continued through November 1991. The flow rate through the reactors was maintained at approximately 10 mL/min. The optimum flow rates were determined from evaluation of metal removal rates in bench scale experiments and the Big Five pilot treatment system (Bolis et al. 1991, Wildeman et al. 1990).

For both the 1990 and 1991 sets of experiments, the flow rates were measured and adjusted regularly. The difference in height between the standing water on top of the substrate and the outlet was measured, as well as the height of the substrate in the reactor in order to assess whether compaction of the substrate occurred during the course of the experiments. Field measurements of pH, Eh, conductivity, and temperature were made on a regular basis. Water sampling and constituent analyses followed procedures established for the Big Five constructed wetland.

1991 Lab Experiments

Hydraulic conductivities of the manure and limestone substrates were also measured in the lab, using both the constant head and a falling head techniques described in Fetter (1988) and EPA Method 9100 (1986). The permeameter used was 45 cm high and 7 cm in diameter. A third substrate, a mixture of manure and hay in a 3:1 ratio was also tested in the lab. This substrate has been utilized by others to evaluate wetlands treatment of acid mine drainage (Euler et al. 1991).

Calculation of Hydraulic Conductivity

Hydraulic conductivity of each reactor substrate was determined from Darcy's Law (Fetter 1988, U.S. EPA 1986). Flow through saturated media is governed by Darcy's Law, as follows:

$$Q = K A \frac{dh}{dl} \qquad (1)$$

where Q = volumetric flow rate, (ml/min)
K = hydraulic conductivity, (cm/sec)
A = cross sectional area, (cm^2)
$\frac{dh}{dl}$ = hydraulic gradient, (cm/cm)

For a constant head system, hydraulic conductivity can be calculated by rearranging equation (1):

$$K = \frac{Q\, dl}{A\, dh} \qquad (2)$$

For a falling head system, hydraulic conductivity is calculated as:

$$K = \frac{L}{t} \ln (h_0/h_2) \qquad (3)$$

where L = length of system, (cm)
t = time for water to flow from h_0 to h_2, (sec)
h_0 = initial water height, (cm)
h_2 = final water height, (cm)

Equation (2) was used to calculate the hydraulic conductivity of the bench scale reactors, and both equations (2) and (3) were used to estimate hydraulic conductivity of the lab experiments.

The mean hydraulic conductivities obtained from the reactors and lab experiments were compared using t tests performed at the 0.05 level of significance.

Results

1990 Bench Scale Results

Hydraulic conductivity measurements are plotted versus time for the National and Quartz Hill Tunnels reactor experiments as shown in Figures 1a and 1b. Both figures present the results from three simultaneously operated reactors that were subjected to varying initial substrate conditions.

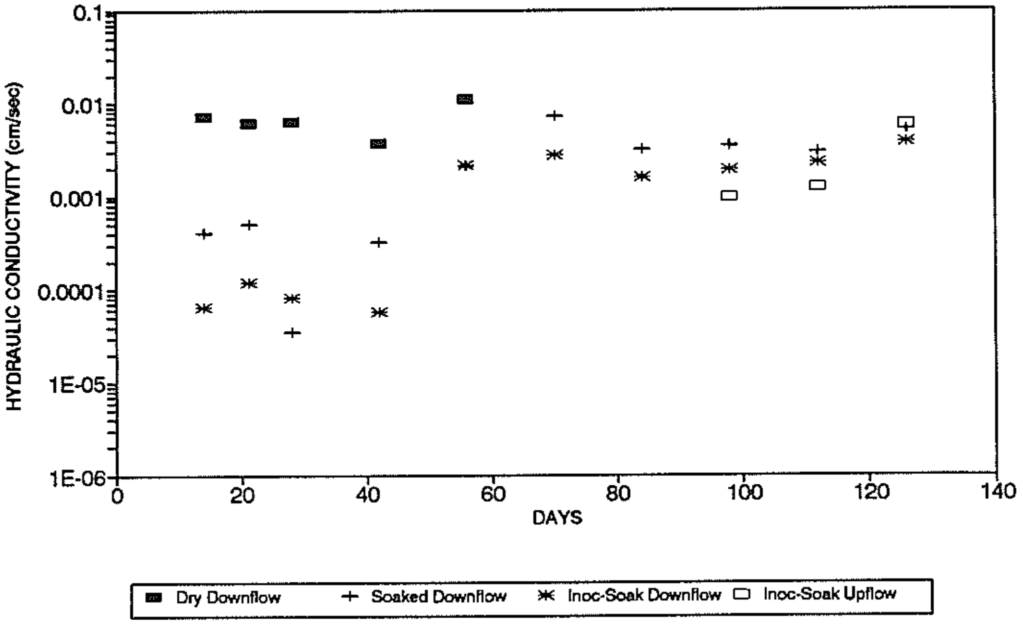
Initially, the hydraulic conductivity of the soaked National reactors was less than 5.0 x 10^{-5} cm/sec for the first 42 days and then increased to stabilize at approximately 5.0 x 10^{-3} cm/sec by day 126. Overall, the dry National reactor shows minor changes in hydraulic conductivity and the soaked downflow reactors shows an increase in hydraulic conductivity over time. The hydraulic conductivity of the initially dry reactor (measured only in the first 60 days) stabilized quickly, averaging approximately 8.0 x 10-3 cm/sec. Statistical analysis indicated no significant difference in hydraulic conductivity between the soaked reactors.

Hydraulic conductivity measurements for the Quartz Hill reactors are shown in Figure 1b. In the initially dry reactors, the hydraulic conductivity varied from 6.0 x 10^{-4} cm/sec to 2.0 x 10^{-3} cm/sec in the first 40 days. Hydraulic conductivity of the soaked reactors was initially lower than that observed in the dry reactor for the first 50 days, ranging from 1.0 x 10^{-4} cm/sec to 5.0 x 10^{-4} cm/sec. Statistical analysis showed no significant difference exists between the soaked and inoculated and soaked substrates during this time period. However, the difference between the average hydraulic conductivity in these reactors and the dry reactor is significant. The hydraulic conductivity in the soaked reactors increased to at least 3.0 x 10^{-3} cm/sec by day 123.

The behavior of the soaked Quartz Hill reactors is similar to that of the soaked reactors of the National Tunnel; hydraulic conductivity in both sets of reactors increased by nearly 1 order of magnitude during the experiment (starting at less than 1.0 x 10^{-4} cm/sec and increasing to approximately 5.0 x 10^{-3} cm/sec by day 132).

An upflow soaked and inoculated reactor was started in place of the dry downflow reactor. Hydraulic conductivity measurements began on days 98 and 89 for National and Quartz Hill, respectively. As shown by the National soaked downflow data, hydraulic conductivity increases over time nearly one order of magnitude. The hydraulic conductivity of the soaked and inoculated upflow reactor (days 98 - 126) is higher that the soaked and inoculated downflow reactor (days 14 - 28). Statistical analysis verified no significant difference between the two configurations.

However, for Quartz Hill, under the same initial substrate conditions, the upflow reactor (days 89 - 123) had lower hydraulic conductivity


(a) NATIONAL TUNNEL-MANURE

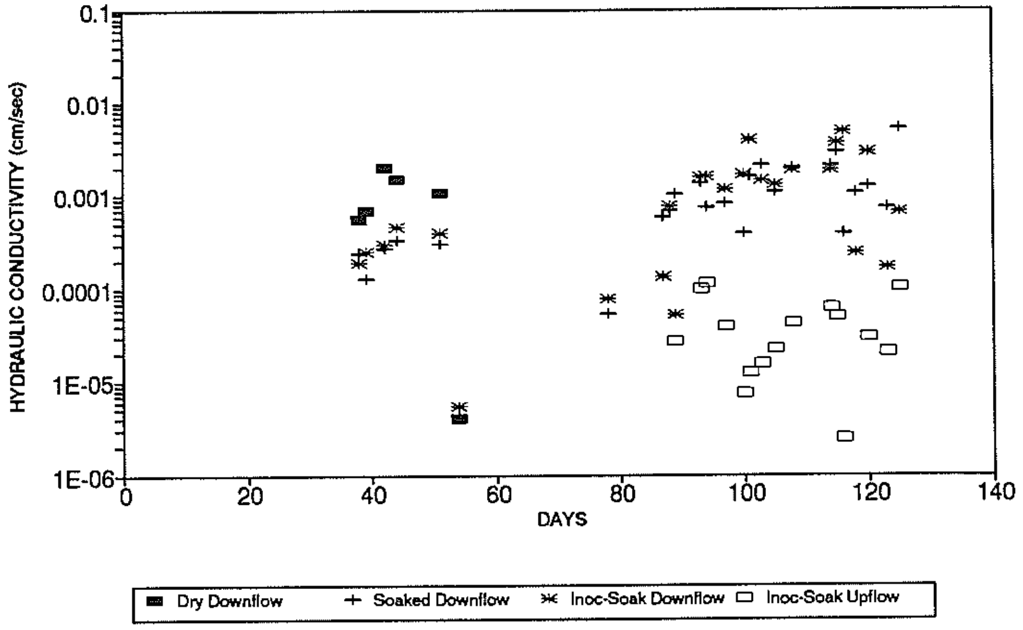

(b) QUARTZ HILL-MANURE

Figure 1. Hydraulic conductivity for the National Tunnel drainage reactors (a) and Quartz Hill drainage reactors (b) with a manure-planter soil substrate operated under three initial substrate conditions in a downflow configuration and one substrate condition in an upflow configuration.

values then the downflow reactor (days 38 - 54). Statistical indicates a significant difference between the hydraulic conductivity values of the two configurations.

The verify to difference in hydraulic conductivity between the dry and soaked reactors, and the observed increase in hydraulic conductivity with time for the soaked substrates, field experiments were performed in 1991 to determine whether 1990 results could be duplicated. Also, laboratory permeameter experiments were conducted to determine how well the values corresponded to the field results.

1991 Bench Scale Results

Figure 2a plots the hydraulic conductivity versus time for the inorganic limestone reactors over 132 days of experimentation. The measured hydraulic conductivities for both the initial dry and initially soaked reactors ranged between 1.0×10^{-3} cm/sec and 1.2×10^{-2} cm/sec. Statistical analysis indicates no significant difference in hydraulic conductivity between the dry and soaked limestone between days 5 through 49, but a difference between days 54 through 132 and 5 through 132. The average hydraulic conductivity for the reactors in days 5 through 49 was 5.4×10^{-3} cm/sec, and 4.98×10^{-3} cm/sec and 2.17×10^{-3} cm/sec for the dry and soaked reactors after days 54.

Substrate samples were taken from both the initially dry and soaked limestone reactors after day 132. Limestone rock sizes of the initially dry reactor ranged from 1/8 inch to 1/2 inch and the initially soaked reactor ranged from 1/16 inch to 1/4 inch. The initially dry reactor substrate compacted approximately 6 cm while the soaked reactor substrate compacted approximately 3 cm.

Hydraulic conductivity of the organic manure reactors versus time is plotted in Figure 2b over 132 days of experimentation. The dry reactor fluctuated between 1.0×10^{-4} cm/sec and 6.0×10^{-3} cm/sec during the first 80 days of experimentation. During the last 50 days the hydraulic conductivity fluctuated between 9.0×10^{-4} cm/sec and 7.0×10^{-3} cm/sec. Hydraulic conductivity of the soaked manure reactor ranged between 4.0×10^{-4} to 1.0×10^{-3} cm/sec for the first 80 days of experimentation, then increased gradually to 6.9×10^{-3} cm/sec. Statistics verify a difference in hydraulic conductivity between dry and soaked substrate from days 5 through 49 and days 54 through 132, but show no difference overall between days 5 through 132.

Substrate samples taken at the end of the experiment from the organic substrate reactors indicate sizes ranging from fines to 1/8 inch. Compaction measurements indicate that throughout the 132 days of experimentation the substrate compacted approximately 1 cm to 2 cm.

1991 Lab Results

The hydraulic conductivity values for constant head and falling head lab experiments for three substrates are shown in Table 2. For comparison, Table 2 also contains the hydraulic conductivity for all field experiments. Lab 1990 and field 1990 represent the Quartz Hill and the National Tunnel experiments, respectively. Lab 1991 represents the permeameter experiments that included both constant head and falling head.

The 1991 lab tests hydraulic conductivity values ranged from 2.0×10^{-3} cm/sec to 7.3×10^{-2} cm/sec. The values shown represent an average of at least three tests. Note that the table shows the range of hydraulic conductivity for each substrate analyzed.

Discussion

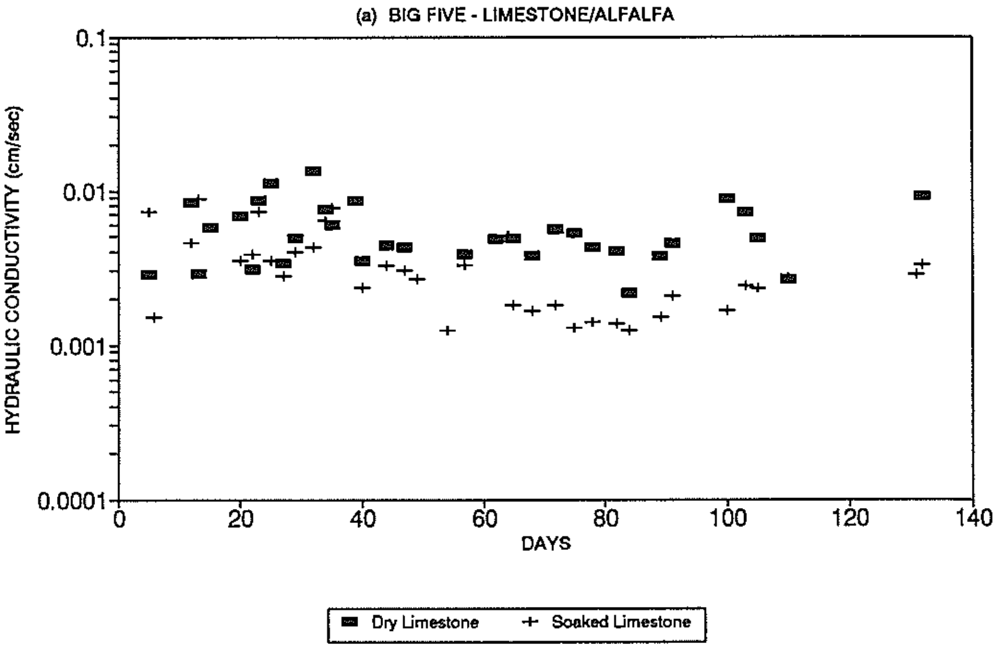
Field Experiments

Figures 1a and 1b show the initially dry substrate has a higher hydraulic conductivity than the soaked substrate. Hydraulic conductivities of the substrates that had been soaked, including the inoculated reactors, increased after about 40 days to values approximately equal to that of the dry substrate.

In the 1991 experiments, the dry limestone hydraulic conductivities remained fairly consistent over time as shown in Figure 2a. Soaked limestone showed a slightly downward trend over time but remains within the same order of magnitude of hydraulic conductivity as the soaked substrate.

The manure used in the 1991 experiments, as shown in Figure 2b, was the same substrate as the 1990 experiment. The hydraulic conductivity of the dry substrate is higher than the soaked substrate but the values for the soaked gradually increase to the same level. This behavior is similar to that observed in 1990.

Studies report that bacterial growth can block the pore spaces in a wetland system e.g., bacterial growth in a wetland system used to treat landfill leachate decreased the hydraulic conductivity by



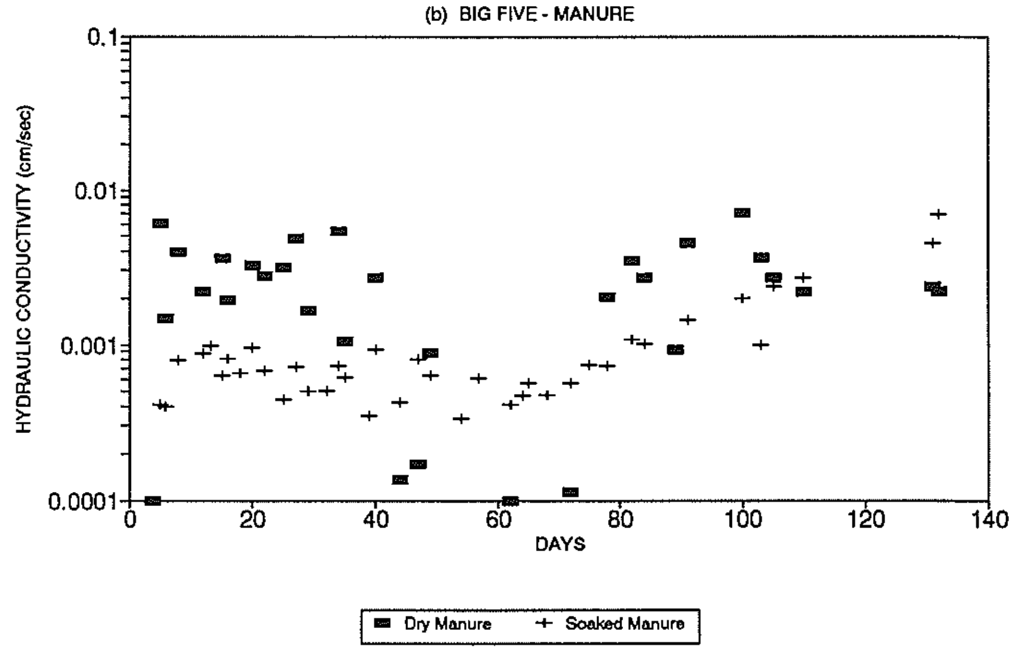


Figure 2. Hydraulic conductivity for the Big Five Tunnel drainage reactors with a limestone-alfalfa substrate (a) and a manure-planter soil substrate (b) operated under two initial substrate conditions in a downflow configuration.

Table 2. Hydraulic conductivity for various substrates, cm/sec.

TEST	TYPE	SUBSTRATE CONDITION	SUBSTRATE		
			Manure	Limestone -Alfalfa	Manure-Hay
LAB 1990[a]	Constant Head	D	$4.0 \times 10^{-6} - 2.0 \times 10^{-3}$	NE	NE
		S	$4.4 \times 10^{-6} - 2.9 \times 10^{-3}$	NE	NE
		IS	$5.6 \times 10^{-6} - 4.9 \times 10^{-3}$	NE	NE
		ISU	$2.5 \times 10^{-6} - 1.2 \times 10^{-4}$	NE	NE
FIELD 1990[b]	Constant Head	D	$3.7 \times 10^{-3} - 1.1 \times 10^{-2}$	NE	NE
		S	$3.5 \times 10^{-5} - 7.2 \times 10^{-3}$	NE	NE
		IS	$5.8 \times 10^{-5} - 3.8 \times 10^{-3}$	NA	NE
		ISU	$9.7 \times 10^{-4} - 5.9 \times 10^{-3}$	NE	NE
LAB 1991[c]	Constant Head	D	4.0×10^{-2}	---[e]	7.3×10^{-2}
		S	---[e]	--[e]	NE
	Falling Head	D	2.1×10^{-2}	2.0×10^{-3}	2.7×10^{-2}
		S	3.0×10^{-3}	---[e]	NE
FIELD 1991[d]	Constant Head	DI	$9.9 \times 10^{-5} - 7.1 \times 10^{-3}$	$2.1 \times 10^{-3} - 1.3 \times 10^{-2}$	NE
		IS	$3.4 \times 10^{-4} - 6.9 \times 10^{-3}$	$1.3 \times 10^{-3} - 8.8 \times 10^{-3}$	NE

[a] LAB 1990 = Quartz Hill bench scale lab experiments.
[b] FIELD 1990 = National Tunnel bench scale field experiments.
[c] LAB 1991 = lab permeameter testing of substrates.
[d] FIELD 1991 = Big Five bench scale field experiments.
[e] No conductivity values could be obtained in the lab.

NE	Not evaluated as part of this experiment.
D	Substrate initially dry, downflow configuration.
S	Substrate initially soaked, downflow configuration.
IS	Substrate initially inoculated, downflow configuration.
ISU	Substrate initially inoculated and soaked, upflow configuration.
DI	Inoculated dry substrate.

50% after 2 weeks (Staubitz et al. 1989). The soaked and inoculated substrate in Figure 1 had anaerobic conditions for 1 week that would allow for a microbial population to become established and thus, lower conductivity. This is also shown in Figure 2b with the soaked manure system. The alfalfa in the limestone substrate also promoted growth of bacteria and may be cause of the minor decrease in hydraulic conductivity of the soaked substrate through time.

Bacterial activity cannot explain all the observed trends in the hydraulic conductivity. The components of the substrate matrix also affect the hydraulic conductivity, specifically the grain size, pore space and permeability. Another explanation for the trends seen in the manure-soil substrate is that organic material swells when it is soaked and this causes the pore space to decrease. This would explain why the soaked substrate has a low initial hydraulic conductivity. However, it does not explain why the hydraulic conductivity increases with time. The hydraulic conductivity of the soaked substrate may increase with time as the fines and loosely attached bacteria are worked out. Also, initial low hydraulic conductivity may be due to a buildup of anaerobic slimes that are clogging the substrate (Watson 1989). As the reactors operate, the slime buildup may be slowly removed, therefore causing the increase in hydraulic conductivity.

Significant fluctuations in the hydraulic conductivity of the dry substrates occurred in the first 40 days of experimentation for both years. This variation may be due to variations in the bacterial population as it becomes established. Additionally, entrapped air, and gases such as CO_2 and CH_4 are generated within the substrate, and may clog pore spaces. Because of the wide variation in hydraulic conductivity, the dry reactors were more difficult to maintain at a constant flow in the 1990 and 1991 field experiments.

The soaked manure substrate yielded the most consistent and easily controlled hydraulic conductivities. A consistent hydraulic conductivity is preferred in subsurface treatment systems, particularly in systems with limited area and volume, as it facilitates attachment of microorganisms to the substrate matrix (Steiner and Freeman, 1989).

Lab Experiments

The 1991 lab experiments show hydraulic conductivities for the inorganic substrate that are comparable to the field results. However, the manure substrate, both soaked and dry, have higher conductivities than their field counterparts. For the lab tests the substrate was soaked overnight. This probably is long enough to cause swelling of the organic material, but it is not a long enough inoculation time for the bacteria. Also, the hydraulic conductivity differences could be due to differences in packing and possible sorting of the substrate constituents.

Comparison to Other Conductivity Studies

The hydraulic conductivity values of substrate or materials used in wetlands wastewater treatment systems shown in Table 1 range from 10 cm/sec to 1 x 10^{-5} cm/sec, depending on the substrates. The reported values of this research range from 1.0 x 10^{-4} cm/sec to 3.0 x 10^{-5} cm/sec for field experiments only. These values are on the lower end of the range of values in Table 1.

Lemke (1989) evaluated the hydraulic conductivity of mushroom compost used in the treatment of mine drainage; downflow hydraulic conductivity values ranged from 2.96 x 10^{-4} cm/sec to 3.5 x 10^{-3} cm/sec. The 1990 and 1991 bench scale data encompass this range. Lemke reported upflow hydraulic conductivity values ranging 1.38 x 10^{-2} cm/sec to 6.65 x 10^{-2} cm/sec. The 1990 upflow hydraulic conductivity ranges from 2.5 x 10^{-6} cm/sec to 5.9 x 10^{-3} cm/sec.

Most of the other reported hydraulic conductivity values in the table were determined using soils and gravel. The hydraulic conductivity of the soils average 3.0 x 10^{-3} cm/sec and the gravels range from 1 x 10^{1} cm/sec to 3.4 x 10^{-3} cm/sec. The pulverized fuel ash (burnt coal waste), used by Copper and Hobson (1989), had a lower hydraulic conductivity than any other substrates listed and exhibited surface flow. The old natural reed beds were reported to have hydraulic conductivity values of 5.0 x 10^{-4} cm/sec, one of the lower values listed in the table. This value suggests that the hydraulic conductivity may decrease over long periods of time.

Finally, lab tests of a homogenous mixture and a sorted substrate show hydraulic conductivity values higher than the other reported values (Staubitz et al. 1989). This is consistent with the 1991 lab tests that were approximately one order of magnitude higher than those values measured in the field experiments.

Summary

Hydraulic conductivity experiments performed on substrates used in subsurface wetlands have generated the following conclusions:

- For both inorganic and organic substrates, the hydraulic conductivity of initially dry substrate fluctuates and is inconsistent, making it difficult to control the flow of mine drainage through the system. These variable values make it difficult to estimate hydraulic conductivity for a dry substrate.
- For primarily organic substrates such as manure-soil, that are soaked prior to applying mine drainage, hydraulic conductivity ranges between 3.3 x 10^{-4} to 9.8 x 10^{-4} cm/sec in the first 50 to 90 days and then gradually increase to approximately an order of magnitude greater, ranging from 1.0 x 10^{-3} to 6.9 x 10^{-3} cm/sec.
- For primarily inorganic substrates such as

the limestone-alfalfa mixture tested, hydraulic conductivity remains fairly constant over time, averaging approximately 1.23 x 10^{-3} cm/sec to 8.8 x 10^{-3} cm/sec.

- Overall, laboratory and field bench scale studies yield hydraulic conductivities ranging from 2 x 10^{-6} cm/sec to 1.0 x 10^{-2} cm/sec for the organic manure substrate. Hydraulic conductivities range from 1.3 x 10^{-3} to 1.3 x 10^{-2} cm/sec for the inorganic limestone substrate.
- A method for estimating the expected range of hydraulic conductivity for a candidate substrate is to perform a constant and/or falling head permeameter measurements on dry substrates and on substrates that have been soaked for one week. The permeameter should be at least 2 liters in volume so that a representative sample of heterogeneous material can be tested. For a highly organic substrate, hydraulic conductivities obtained in the laboratory may be higher than the values determined in the field.

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